Title: Electroweak Baryogenesis and the LHC

Date: Mar 03, 2015 01:00 PM

URL: http://pirsa.org/15030102

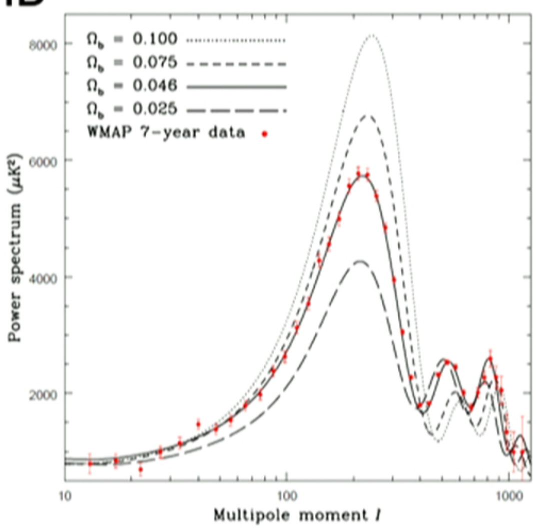
Abstract: <p>It is not known how to explain the excess of matter over antimatter with the Standard Model. This matter asymmetry can be accounted for in certain extensions of the Standard Model through the mechanism of electroweak baryogenesis (EWBG), in which the extra baryons are created in the early Universe during the electroweak phase transition. In this talk I will review EWBG, connect it to theories of new physics beyond the Standard Model, and show that in many cases the new particles and interactions required for efficient EWBG can be discovered using existing and expected data from the LHC.</p>

Baryons > Antibaryons

$$\Omega_B = 0.0486 \pm 0.0011$$

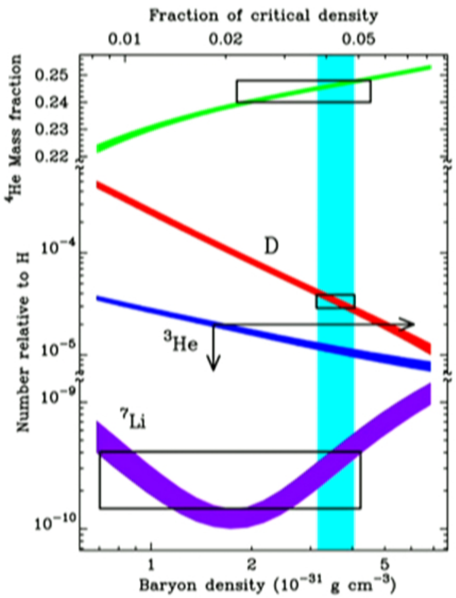
$$\eta \equiv \frac{n_B}{n_\gamma} \simeq (7.04)\frac{n_B}{s} \simeq 6.1 \times 10^{-10}$$

CMB



[Garrett+Duda '10]

BBN



[Cyburt *et al.* '97]

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Baryogenesis Ingredients [Sakharov '67]

1. Baryon Number Violation
2. C and CP Violation
3. Departure from Equilibrium

Ingredients are not enough:

$+$

$\neq$

A mechanism for baryogenesis is needed.

Electroweak Baryogenesis

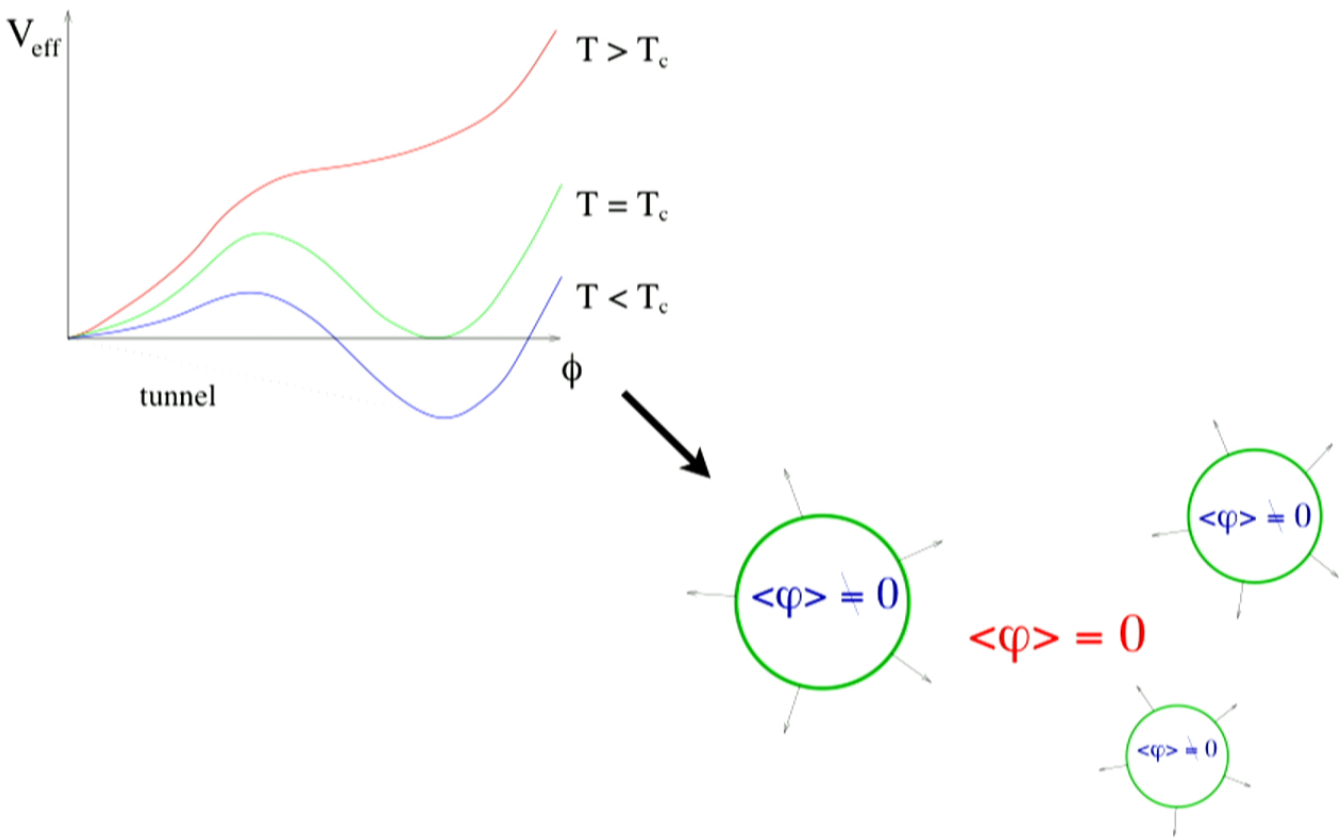
[Kuzmin, Rubakov, Shaposhnikov '87]
[Cohen, Kaplan, Nelson '90-'95]

Three Steps:

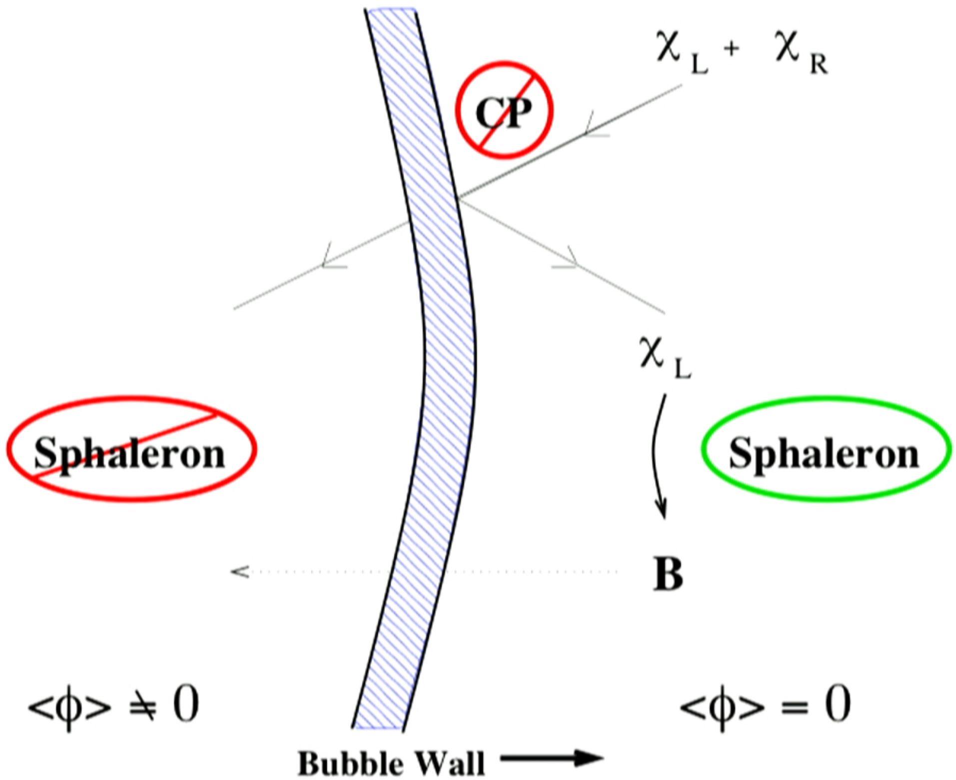
1. First-order EW PT produces expanding bubbles.
2. C and CP violation near the bubble wall induce chiral asymmetries.
3. Electroweak sphalerons convert this to a baryon charge.

Could this explain baryogenesis within the SM?!

Non-Equilibrium: Bubbles



C and CP Violation



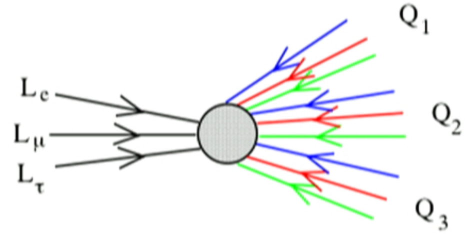
Baryon Creation

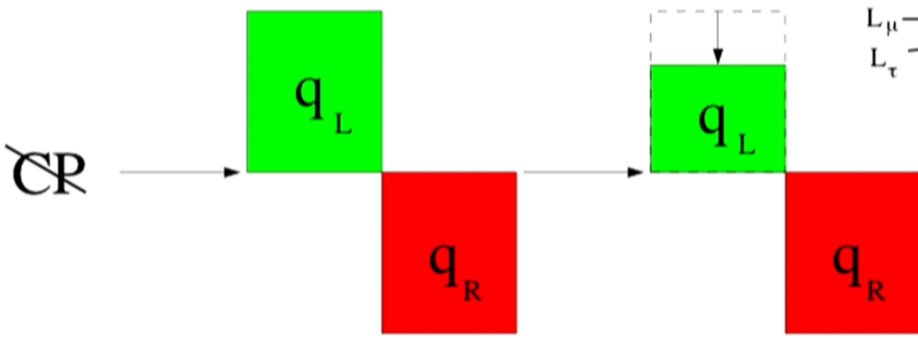
Sphaleron = non-perturbative $SU(2)_L$ thermal transition.

Violates (B+L) by 3 units.

Active in the unbroken phase.
Suppressed in the broken.

$$\Gamma/V \sim \begin{cases} (\alpha_w T)^4 \\ T^4 \exp(-8\pi\langle H\rangle/g_w T) \end{cases}$$





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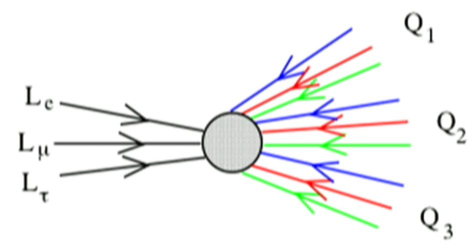

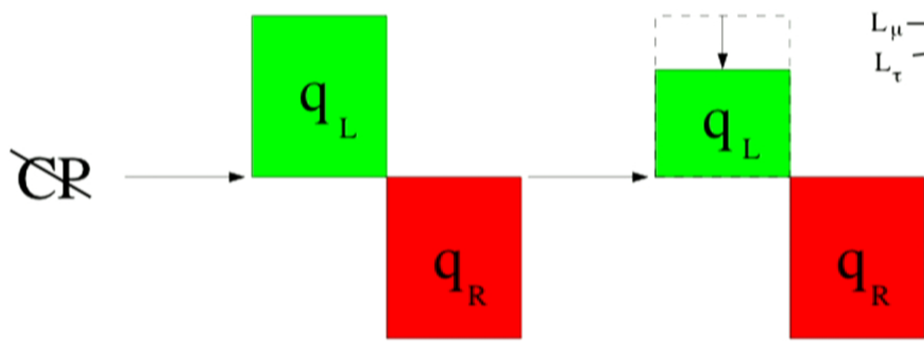

EWBG in the Standard Model

- It doesn't work for two reasons:
  1. The EW PT is not first order for m_h = 125 GeV.
     [Kajantie, Laine, Rummukainen, Shaposhnikov '98]
  2. Not enough effective CP violation.
     [Gavela, Hernandez, Orloff, Pene'94; Huet + Sather '95]

- EWBG could work with new physics.
  e.g. Minimal Supersymmetric Standard Model (MSSM)

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EWBG Beyond the Standard Model

- Fixes:

  1. New matter coupling to the Higgs for a first-order PT.

     e.g. light scalar top (stop) in the MSSM

     [Carena, Quiros, Wagner '96; Delepine, Gerard, Gonzalez Felipe, Wyers '96]

  2. New sources of CP violation from soft terms.

     e.g. phases from soft SUSY breaking terms

     [Carena, Quirós, Riotto, Vilja, Wagner '97; Cline + Kainulainen '97]

EWBG Beyond the Standard Model

- New physics for EWBG is being tested now:
  - LHC measurements constrain new Higgs couplings.
  - EDM searches limit new phases.

- I will illustrate this with the current status of EWBG in the Minimal Supersymmetric extension of the SM (MSSM).
- Similar results also apply to other extensions of the SM.

New Sources of CP Violation (MSSM)

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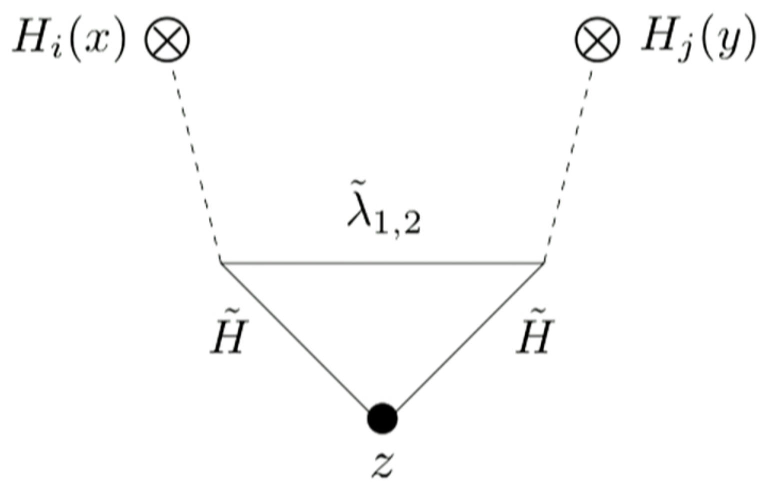
CP Violating Sources

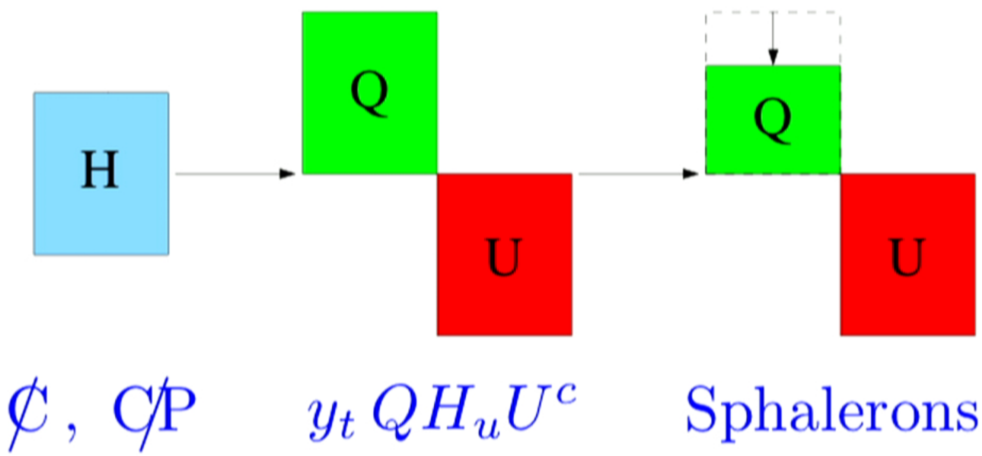
MSSM: Charginos and Neutralinos $(\widetilde{H}_u, \widetilde{H}_d, \widetilde{W}^a, \widetilde{B}^0)$



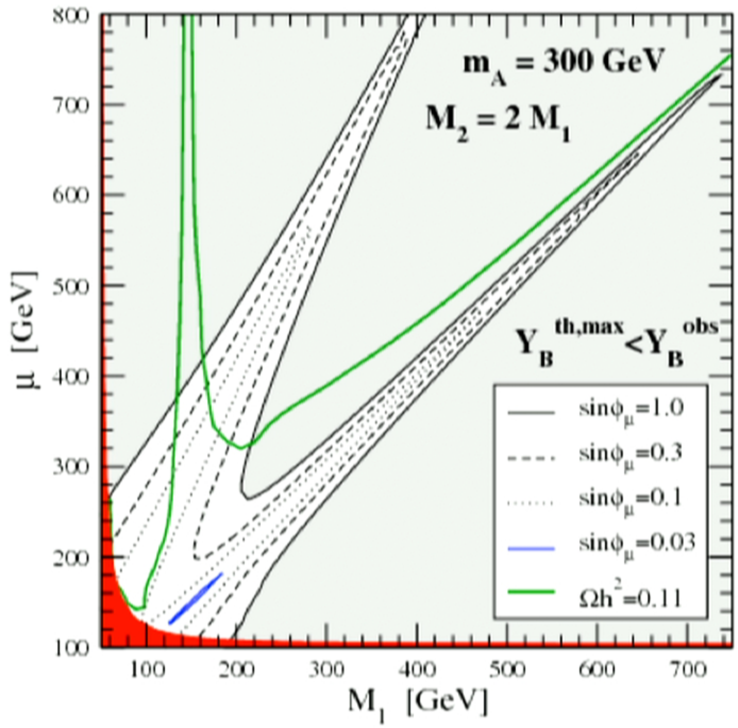
$$
\begin{aligned}
S^{\tilde{H}}_{CPV} &= \partial_0 J^0_{\tilde{H}}(z) \\
&\propto Im(\mu\, M_i)\, \partial_z f(v_u(z), v_d(z))
\end{aligned}
$$

Transfer of Sources to B

- Higgsino source is transferred to tops and stops.
- LH asymmetries bias weak sphalerons to make B.
- (Quark asymmetries are washed out by strong sphalerons.)



Results [Cirigliano, Li, Profumo, Ramsey-Musolf '09]

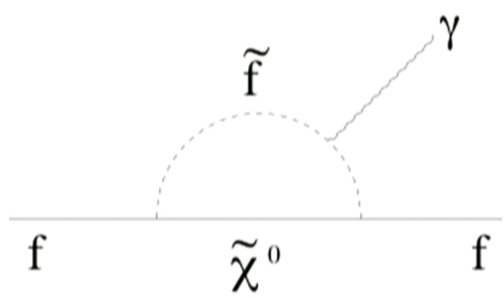


$$M_{1,2} \; = \; \text{gaugino soft mass parameter}$$

$$\mu = \; \text{Higgsino mass parameter}$$

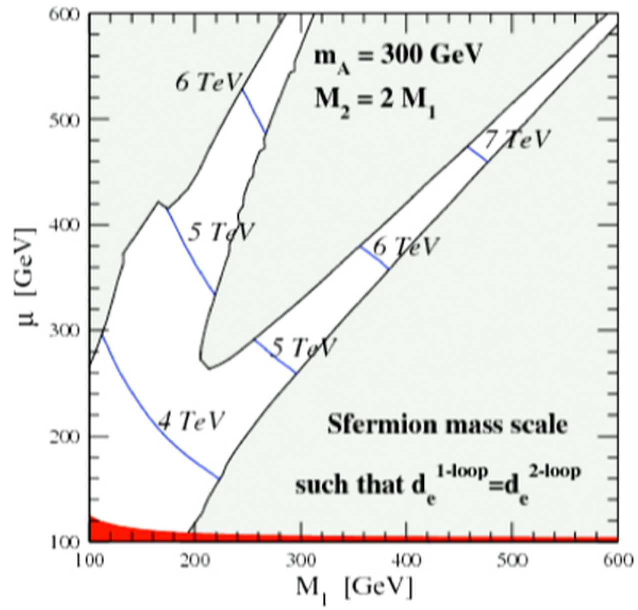
Electric Dipole Moments (EDM)

- One loop:



$+ \ldots$

[Cirigliano, Li, Profumo, Ramsey-Musolf '09]

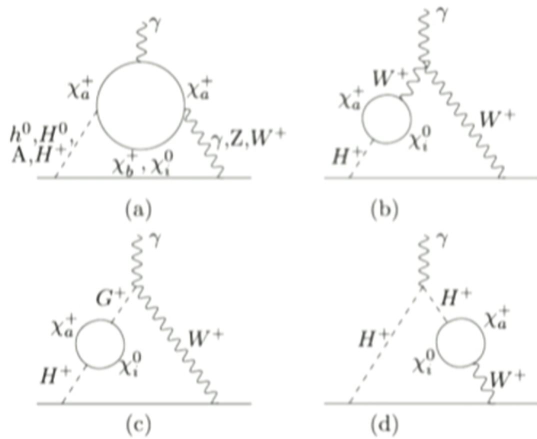


- Decouples for $m_{\tilde{f}} \gtrsim 10\,\mathrm{TeV}$.

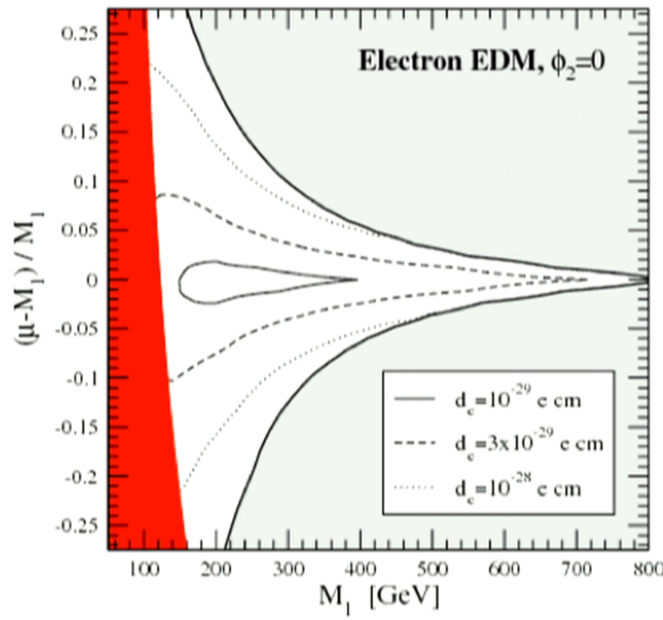
Electric Dipole Moments (EDM)

- Two loop:

  [Chang, Keung, Pilaftsis '98; ...]



[Cirigliano, Li, Profumo, Ramsey-Musolf '09]



- Does not decouple!
- ACME: $d_e < 8.7 \times 10^{-29}\,\mathrm{e\ cm}$

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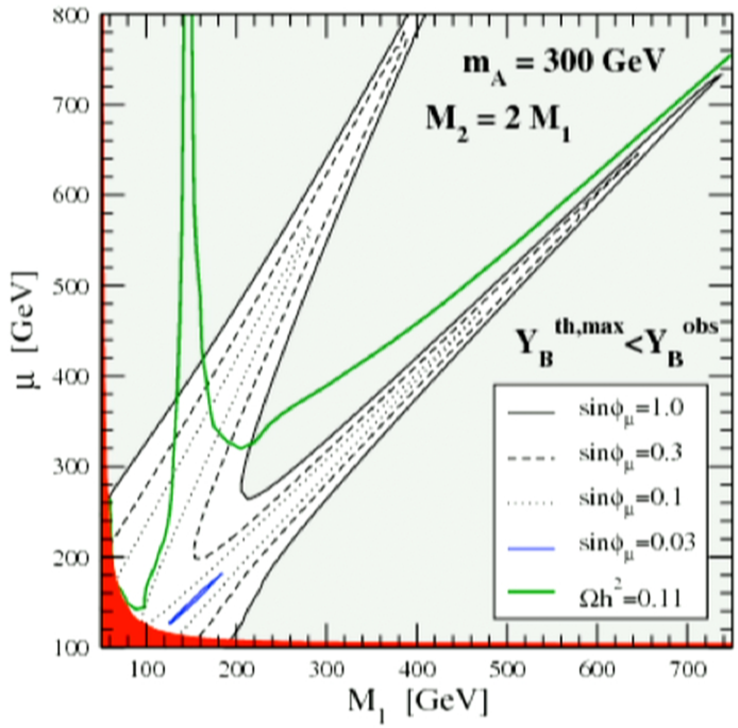
Results [Cirigliano, Li, Profumo, Ramsey-Musolf '09]



$$M_{1,2} = \text{gaugino soft mass parameter}$$

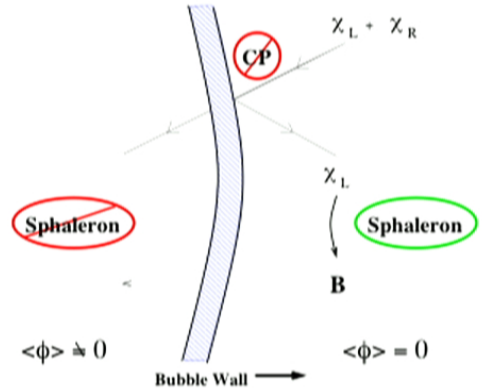
$$\mu = \text{Higgsino mass parameter}$$

A Strongly First-Order Electroweak Transition (MSSM)

Phase Transition "Strength"

- Electroweak PT must be strongly first order to prevent sphaleron washout of B within the broken phase.

$$\Gamma/V \ \sim \ T^4 \exp(-8\pi \langle H \rangle / g_w T)$$



- For bubble nucleation close to the critical temperature,

$$\frac{\text{``}\langle H_c \rangle\text{''}}{T_c} \gtrsim 1.0 \ .$$

[Bochkarev, Kuzmin, Shaposhnikov '91; Patel, Ramsey-Musolf '11]

Light Stops

- MSSM: a light stop drives the first-order phase transition
- Stop mass matrix:

$$\mathcal{M}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + D_L & m_t X_t^* \\ m_t X_t & m_{U_3}^2 + m_t^2 + D_R \end{pmatrix}$$

- Mass eigenstates: $\tilde{t}_1, \tilde{t}_2$ with $m_{\tilde{t}_1} \leq m_{\tilde{t}_2}$.

  Mixing angle: $\theta_{\tilde{t}}$.

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Light Stops and the EW Phase Transition

- Assume $m_{U_3} \ll m_{Q_3}, m_A$.

$$-\mathscr{L}_{eff} \supset m_U^2 |\tilde{t}_1|^2 + Q|H|^2|\tilde{t}_1|^2$$

with

$$m_U^2 \simeq m_{U_3}^2$$

$$Q \simeq |y_t|^2 \sin^2\beta \left(1 - \frac{|X_t|^2}{m_{Q_3}^2}\right) + \frac{1}{3} g'^2 \cos 2\beta$$

[Carena, Nardini, Quirós, Wagner '08]

- Thermal effective potential:

$$V_{eff}(\varphi,T) \simeq -(\mu^2 - \xi\,T^2)\,\varphi^2 - \frac{T}{4\pi}\left[m^2_{\tilde{t}_1}(\varphi,T)\right]^{3/2} + \frac{\lambda}{4}\varphi^4$$

where

$$m^2_{\tilde{t}_1}(\varphi,T) \simeq Q\,\varphi^2 + \underbrace{m^2_U + \xi\,T^2}_{\delta m^2}$$

- Large Q , $\delta m^2 \to 0$ yield a strongly first-order transition.

$$\mathrm{Strength}(\delta m^2 = 0) \;\sim\; \frac{``\langle\varphi_c\rangle''}{T_c} \;\sim\; \frac{Q^{3/2}}{\lambda} \;\gtrsim\; 1$$

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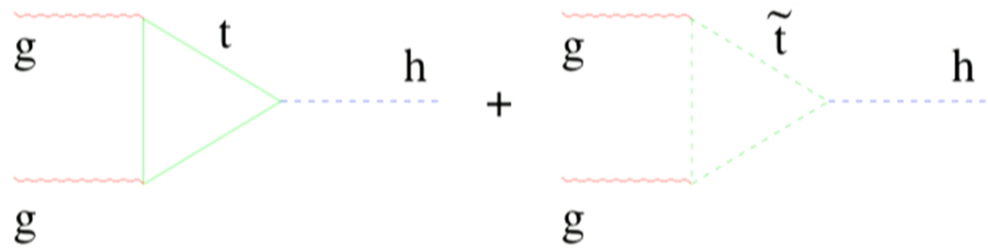
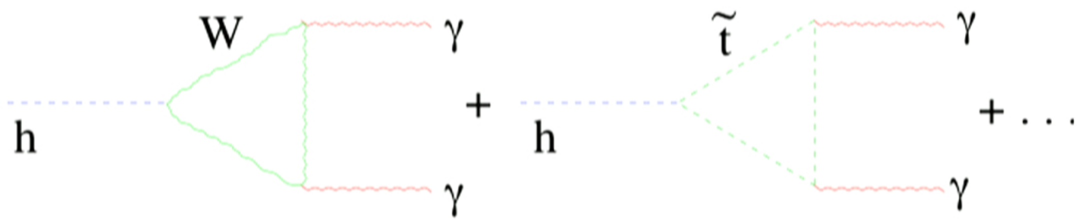
Light Stops and the Higgs

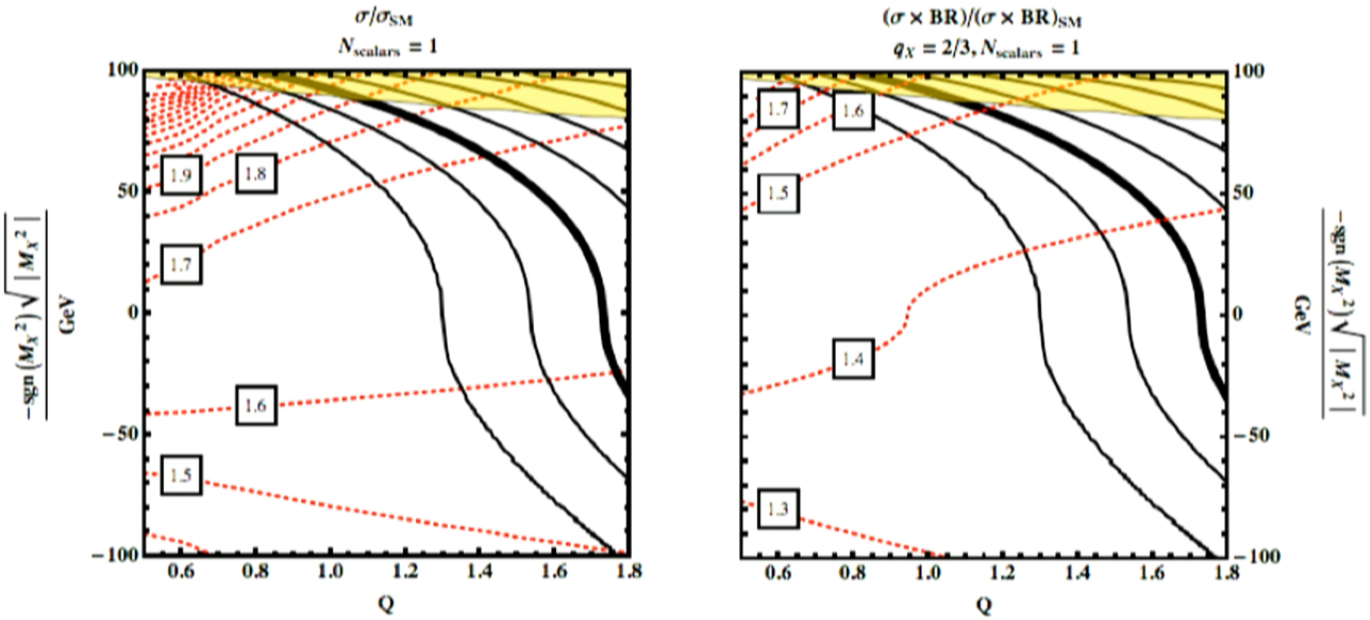
$\sigma(gg \to h^0)$: constructive with top loop for $Q > 0$.



$\Gamma(h^0 \to \gamma\gamma)$: destructive with W loop for $Q > 0$.



Phase Transition vs. Higgs Rates



[Menon, DM '09; Cohen, DM, Pierce '12]

- Enhanced $\sigma(gg \to h)$.
  Suppressed $BR(h \to \gamma\gamma)$, enhanced $\sigma \times BR(h \to \gamma\gamma)$.

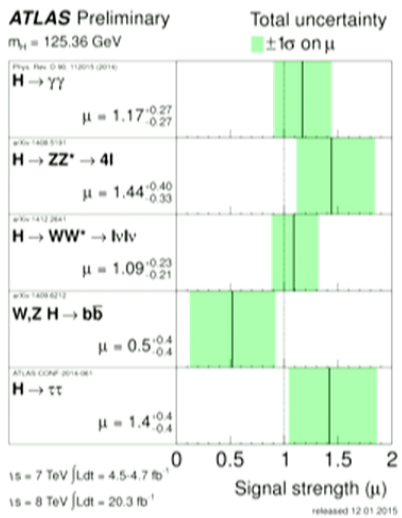
Phase Transition vs. Higgs Rates

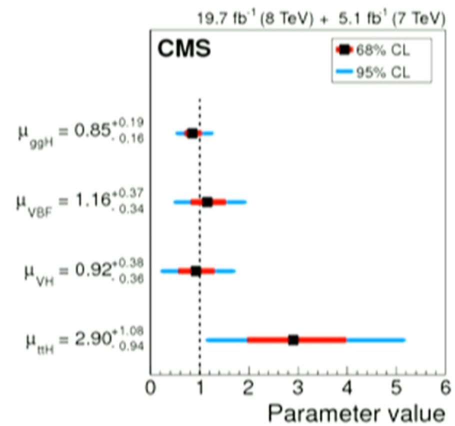
- MSSM EWBG: [Menon, DM '09; Cohen, DM, Pierce '12]

$$\sigma(gg \to h) \; \gtrsim \; 1.6 \times SM$$

$$\sigma \times BR(h \to \gamma\gamma) \; \gtrsim \; 1.3 \times SM$$

- Inconsistent with measured Higgs rates.





[Curtin, Jaiswal, Meade '12; Katz + Perelstein '14]

- Caveats:

    1. Interference with other superpartners (stau, chargino), or invisible decays to neutralinos change Higgs rates.
    [Carena, Nardini, Quirós, Wagner '12]

    2. Lattice studies find a stronger phase transition than perturbative calculations.
    [Laine, Nardini, Rummukainen '13]

    But $m_{\tilde{t}_1} \lesssim 155\,\mathrm{GeV}$ still seems to be required.

- Direct stop searches?

  [Kumar, DM '12; Delgado, Giudice, Isidori, Pierini, Striumia '12]

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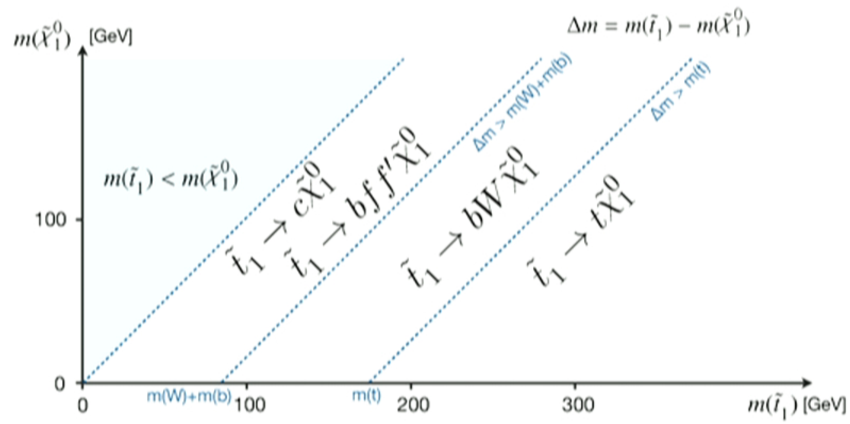
Direct Stop Searches: Light Stop Decays

- Two Body: $\tilde{t} \to t\,\chi_1^0, \qquad \tilde{t} \to b\,\chi_1^+$
- Three/Four Body: $\tilde{t} \to b\,\chi_1^0\,W^{+(*)}$
- Flavor Violating: $\tilde{t} \to c\,\chi_1^0$
- Generally, 2B > 3B > 4B, FV.



[ATLAS]

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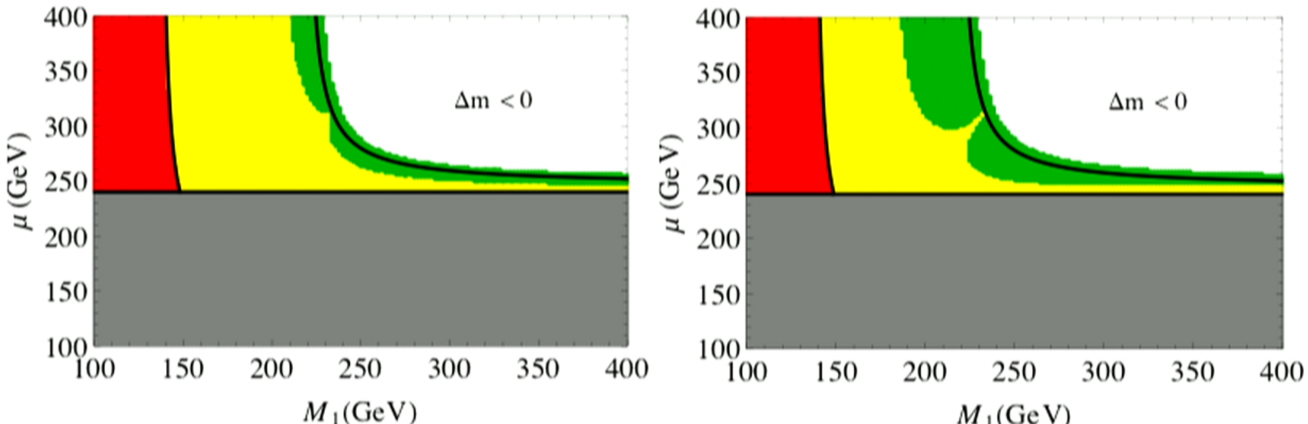
Light Stop Decays

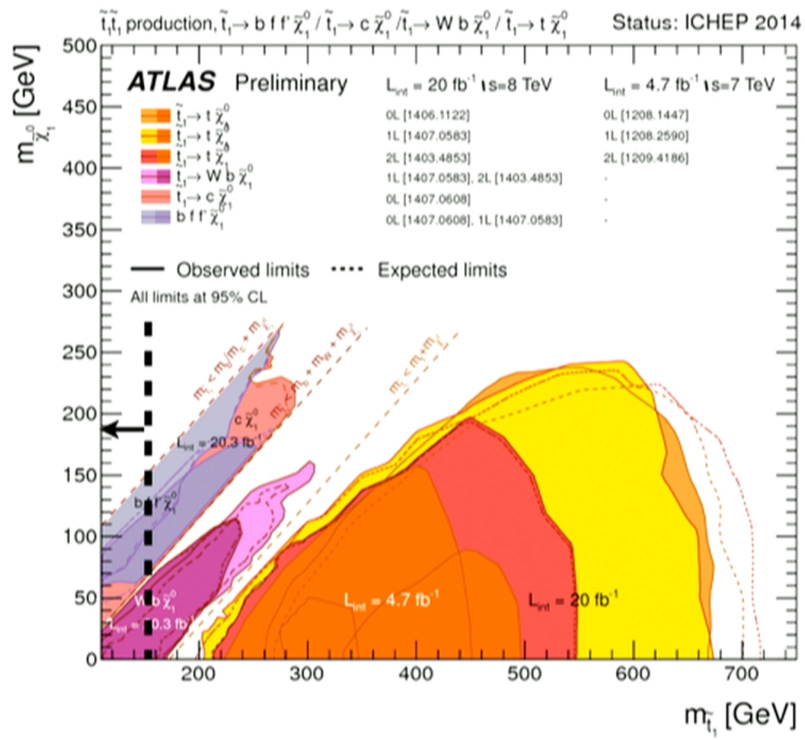
- Two Body vs. Flavor Violating depends on details. Assume Minimal Flavor Violation. [d'Ambrosio, Guidice, Isidori, Strumia '02]
- Decays for $m_{\tilde{t}_1} = 225\,\mathrm{GeV},\ \tan\beta = 10,\ M_2 = 350\,\mathrm{GeV}$:



$\cos\theta_{\tilde{t}} = 0.1$ $\cos\theta_{\tilde{t}} = 0.7$

- 4B dominates over FV except at small mass splitting.

Direct Stop Searches at the LHC



- LHC searches rule out the light stop for MSSM EWBG

[Kumar, DM '12; Delgado, Giudice, Isidori, Pierini, Striumia '12]

- More Caveats:

  1. Searches assume stops decay promptly.
     4B and FV modes are frequently displaced.*
     [Hiller+Nir '08]

  2. Weaker limits with RPV?
     [Evans+Kats'12]

* LHC searches for long-lived stops rule out $m_{\tilde{t}} \lesssim 600\,\mathrm{GeV}$.

[CMS 1205.0272]

EWBG in Other Theories

General EWBG Implications [Curtin, Meade, Yu '14]

1. A strongly first order electroweak phase transition.
   ⇒ new physics to modify the (thermal) Higgs potential

   ⇒ look for deviations in Higgs production and decay

   ⇒ search directly for new states connected to the Higgs

2. New sources of CP violation.
   ⇒ generate asymmetries that bias sphalerons

   ⇒ should be enhanced by the varying Higgs background

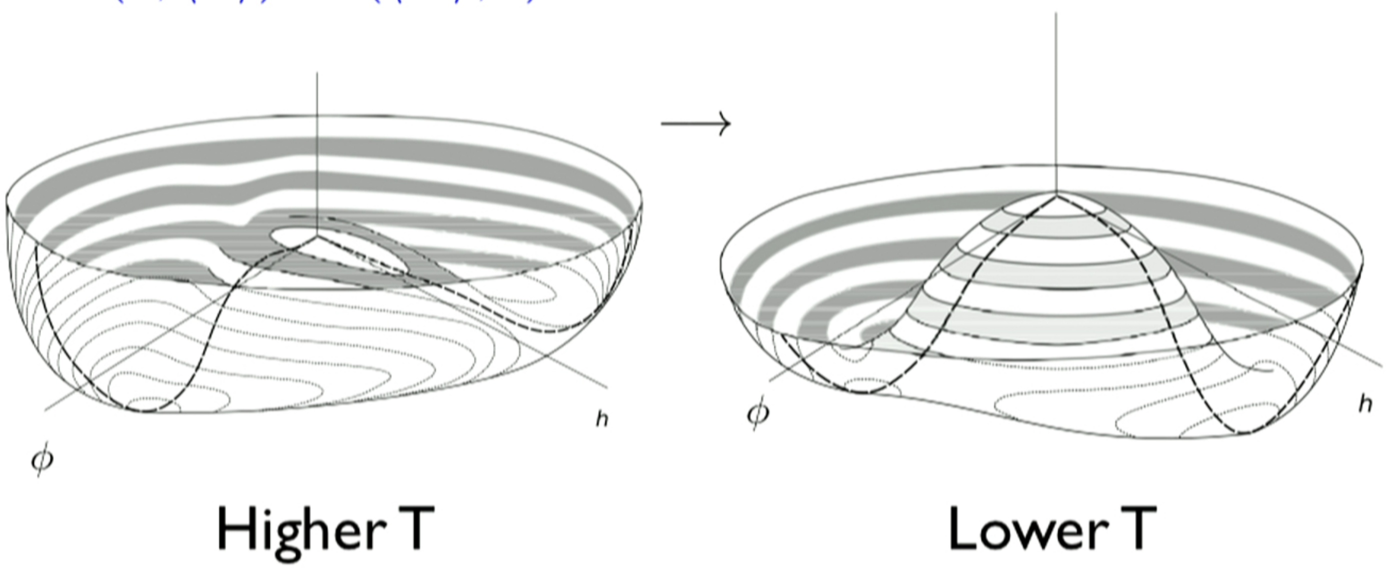
   ⇒ try to measure electric dipole moments (EDM)

   ⇒ search directly for new states

A Loophole?

[Patel+Ramsey-Musolf '12; Blinov, Kozaczuk, DM, Tamarit '15]

- Two electroweak doublets H and Φ .
- Φ gets a VEV in a strongly first-order phase transition.
- $(0, \langle\Phi\rangle) \to (\langle H\rangle, 0)$ in a later transition.



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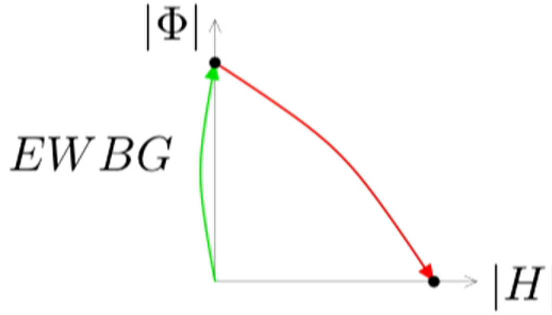

- EWBG happens in the first transition.
- New physics need only couple to Φ , not H.

Note Quite a Loophole

[Patel+Ramsey-Musolf '12; Blinov, Kozaczuk, DM, Tamarit '15]

- Requirements: Φ
  - Φ develops a VEV before H, strongly first-order.
  - $(0, \langle\Phi\rangle) \rightarrow (\langle H\rangle, 0)$ transition completes efficiently.
  - Sphaleron suppression remains, $\langle\Phi\rangle^2 + \langle H\rangle^2 \gtrsim T^2$.
- These conditions typically imply new charged particles with masses below about $m_\Phi \lesssim 150\,\mathrm{GeV}$.
- On the edge of what can be probed by the LHC.

[Liu, Shuve, Weiner, Yavin '13]

Summary

- MSSM EWBG is seriously constrained:
  - EDM bounds are challenging.
  - Light stop, $m_{\tilde{t}} \lesssim 155\,\mathrm{GeV}$, for a first-order EWPT.
  - Very hard to satisfy Higgs rates and direct searches.

- It can still work in extended scenarios ({N}MSSM, Rsym).
- Places to look:
  - EDM searches.
  - Deviations from SM Higgs rates, new scalars.